CONSTRUCTION AND VALIDATION OF SMALL MOBILE WIND TUNNELS FOR STUDYING AMMONIA VOLATILIZATION

J. J. Meisinger, A. M. Lefcourt, R. B. Thompson

ABSTRACT. *Ammonia volatilization is a major nitrogen (N) loss process for surface applied manures and urea fertilizers. Ammonia volatilization is a complex phenomenon requiring specialized research equipment to gather valid scientific data, which is essential for developing management practices to minimize N losses from farms and N inputs to neighboring ecosystems. The objectives of this work were: i) to describe a revised version of the small mobile wind–tunnels originally reported by Lockyer, and ii) to assess the ability of these wind tunnels to quantitatively recover ammonia lost from dilute solutions. The design, construction, cost (about $4000 each), physical calibration, and operation of the wind tunnels are described. The tunnels consist of two connected parts: i) a transparent plastic canopy which covers a 1–m^2 treatment area, and ii) a sheet–metal cylinder, which houses an adjustable speed motor with attached fan blade and an air sampler to monitor ammonia volatilization. Two ammonia loss–and–recovery experiments were conducted at constant wind speeds of 0.5 and 1.0 m s^{-1} to assess tunnel performance. Mean ammonia recoveries were 104±6% at 0.5 m s^{-1} and 104±18% at 1.0 m s^{-1}. These results demonstrate that the wind tunnels can be valid tools for collecting volatilized ammonia and for making relative comparisons among N management treatments. Obtaining valid comparison of different management treatments is essential for the development of improved N management practices that minimize ammonia losses from manures or fertilizers.*

Keywords. Ammonia, Volatilization, Wind tunnel, Manure, Urea.

Ammonia volatilization is a major nitrogen (N) loss process for surface applied manures and urea fertilizers. Volatilized ammonia causes inefficiency and uncertainty for N management on farms, and contributes to N enrichment of natural ecosystems. Ammonia volatilization is a complex phenomenon involving both chemical conversion of ammonium–N to dissolved ammonia gas, and physical transport of the ammonia gas into the air. A large number of environmental and management factors influence ammonia loss under field conditions (Freney et al., 1983). Studying ammonia volatilization requires specialized research equipment that allows perturbations of the physical factors (e.g., tillage, residue cover), the chemical conditions (e.g., manure composition, chemical amendments), and the environmental factors (e.g., air movement) that influence ammonia loss. Gathering sound ammonia volatilization data is essential for developing management practices to minimize N losses from farms and the associated N deposition in neighboring ecosystems.

Ammonia volatilization from field soils has been studied by three general approaches: i) micrometeorology, ii) covered chambers, and iii) small wind–tunnel techniques. Micrometeorological methods are widely accepted as the most accurate method for quantifying ammonia losses under field conditions (Denmead, 1983; Harper, 1988; Ryden and McNeill, 1984; Wilson et al., 1983, Chambers et al, 1997). However, micrometeorological methods require large areas of uniform topography to obtain stable wind profiles (e.g., fetches >200 m) and also need relatively large areas for treatment application (e.g., 20– to 50–m diameter circles). The need for large areas commonly prevents replication and limits investigations to only one treatment. Covered chambers (Kissel et al., 1977; Ferguson et al., 1988; Svensson, 1994) have the advantage of replication, comparison of several treatments, no site restrictions, and are relatively inexpensive. However, the chambers are usually very small (0.1 to 0.2 m^2) which restricts their usefulness for studying factors that are non–homogenous over small areas. Additionally, the chambers artificially restrict air exchange between the soil surface and the outside air. This problem can be reduced with short closure times, although sampling continuity is disrupted.

Small wind tunnels (Lockyer, 1984; Braschkat et al., 1993; Lorenz and Steffens, 1997) offer advantages of minimal environmental disturbance, study of several treatments, replication, measurement over larger areas (0.8 to 1.0 m^2), and the ability to make relative comparisons among treatments. Disadvantages of wind tunnels include higher costs than small chambers and, because wind speeds are controlled, an imperfect quantitative extrapolation to

natural conditions. However, Ryden and Lockyer (1985) found good agreement between wind tunnel ammonia losses and micrometeorology losses if wind speeds in the tunnels were matched to ambient wind velocities. The small wind–tunnel system described by Lockyer (1984) is a versatile design used by a number of European research groups (e.g. Klarenbeek and Bruins, 1991; Sommer et al., 1993; Moal et al., 1995). However, the mobility of the Lockyer (1984) tunnels was restricted by housing each tunnel's control system, pumps, and flow meters in a single trailer. The current modification of the original design was undertaken to improve mobility, to utilize materials readily available in the United States, and to incorporate components that have been improved since 1984. The objectives of this research were: i) to describe a revised mobile version of the small wind tunnels originally reported by Lockyer (1984), and ii) to assess the ability of these wind tunnels to quantitatively recover ammonia lost from dilute solutions.

## CONSTRUCTION MATERIALS AND METHODS
GENERAL DESCRIPTION

The basic design of the wind tunnels is given by Lockyer (1984). Each wind–tunnel system consists of a transparent plastic canopy covering 1.0 m² (fig. 1) and an attached sheet metal cylinder which houses a variable speed dc motor and attached fan to draw air across the enclosed treatment area (fig. 2). The tunnel also contains an air–sampling device and an anemometer to continuously monitor wind speed. Gas scrubbing bottles with dilute phosphoric acid and small vacuum pumps are used to trap ammonia from the entering and the exiting air streams. Additional equipment consist of a data logger, flow meters, electrical connections, and vacuum lines. The mobility of the original wind–tunnel system was improved by: (i) installing the control units, electrical connections, and the anemometer module for each tunnel in an all–weather enclosure mounted directly onto the tunnel (fig. 2), and (ii) locating air pumps and associated flow meters in an enclosure placed alongside the tunnel. This arrangement allows each tunnel to be an independent functional unit. Ammonia losses from the treated area are calculated from the ammonia concentrations in the inlet and outlet air streams and the airflow through the tunnel.

CONSTRUCTION AND CALIBRATION

Design and construction details are given in figure 2 and table 1. A total of six tunnels were constructed. The costs in table 1 that pertain to custom fabrication and shared usage equipment (e.g., data logger) were pro–rated over the six tunnels. The clear plastic canopy (fig. 1) is made of
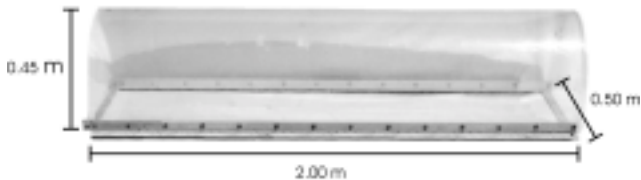
Figure 1. Canopy section of wind–tunnel system with attached 90° aluminum angle base frame.
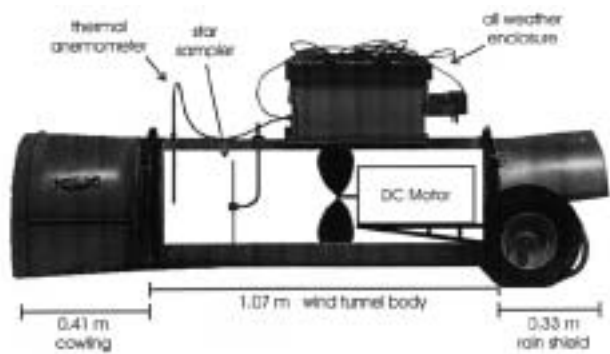
Figure 2. Side view of mobile wind–tunnel unit showing adjustable speed dc motor, air sampler (star–sampler), anemometer, and enclosure to house dc control unit and anemometer module.

polycarbonate and encloses an area of 0.5 × 2.0 m with a height of about 45 cm. The polycarbonate sheet is flexed into an inverted "U" shape, producing a constant cross–sectional area within the canopy. The polycarbonate is permanently attached to a rectangular base frame covering 1 m² which was made from 90° extruded aluminum angle measuring 5 × 5 × 0.3 cm (thickness). The frame of the canopy is normally anchored to the ground with tent pegs.

Table 1. Materials and approximate costs (1996 US$, rounded to $10) for a single wind tunnel.[a]

Item and Brief Description	Approx. Cost ($)
Canopy	
Polycarbonate sheet (122 × 244 × 0.15 cm)	60
90° angle frame, aluminum (5 × 5 × 0.3 cm, 5 m)	60
Wind Tunnel	
Sheet metal duct & cowling, 18 gauge, custom fabrication, pro–rated for construction of six wind tunnels	610
Variable speed dc motor (2 hp, 220 V, 10 amp)	600
Fan blade, aluminum, custom fabrication	220
Motor mount, flat steel and angle iron frame	50
Wheels (2), pneumatic	50
Sampling and Electrical Control	
Variable speed dc motor control	150
Star sampler and mounting	75
Gas scrubbing bottles (2), 125 and 250 mL, w/coarse frit	230
Vacuum pump, 110 V, dual diaphragm	160
Flow Control and Monitoring	
Gas flow meters (2), 1 high resolution, 1 standard	250
Thermal anemometers, w/ power supply, general purpose	680
Data logger, pro–rated for use with six tunnels	350
Electrical and Miscellaneous	
Electrical cable, outdoor 220 V and 110 V (15 m lengths)	105
Electrical plugs and receptacles (220 V and 110 V)	90
Water tight encl. for anemometer, dc controller, etc.	300
Hardware: handles, nuts and bolts, etc.	10
Tubing, Teflon lined and tygon	30
Warming blankets for condensation prevention in canopy	10
Wind breaks, plywood, steel rods	30
Approximate Total Cost	4120

[a] Local labor costs are not included except where noted for custom fabrication of the item.

The 18 gauge sheet metal fan housing has an internal diameter of 40.6 cm, length of 107 cm, and is held rigid by a preformed round angle–iron strap on each end. The fan housing is joined to the canopy by a custom fabricated 18 gauge sheet metal cowling which forms the transition from the inverted "U" shaped canopy to the round cross–section of the fan housing. The cowling is bolted to the fan housing through the round angle–iron strap (fig. 2). The cowling and polycarbonate canopy are attached through a 5–cm overlapping edge that is sealed with duct tape.

The fan housing contains a variable speed motor and fan, an anemometer, and a cross–sectional air–sampling device. These devices are mounted in the tunnel as shown in figure 2. The 1.5–kW (2–hp) variable speed dc motor (General Electric Co., model 5CD123UE002B, Baltimore, Md.) is mounted on an angle–iron support and drives a custom fabricated 36–cm diameter aluminum impeller (Continental Fan Mfg. Inc., Buffalo, N.Y.) with five blades set at a $15°$ pitch. The variable speed motor and fan allow air velocities to vary from 0.3 to 5 m s^{-1}. Normal constant speed operating ranges are 0.5 to 1 m s^{-1}, but the higher velocity capabilities give the potential to mimic natural wind speeds. The dc current is provided by a rectifier and potentiometer unit (Dart Controls Inc., model 250G, Zionsville, Ind.) mounted inside a weather–tight box that converts local 220–V ac to the selected dc power requirement. Wind speed is measured by a thermal (hot–wire) anemometer (AirFlow Tech. Prod. Inc., model 8455, Netcong, N.J.) mounted in the center of each tunnel which monitors wind speeds every 10 s. Air velocities are transmitted and stored in a data logger (Campbell Scientific, model CR21X, Logan, Utah) and averaged over 15–min intervals. The gas–sampling device is a "star sampler" with six equidistantly spaced stainless steel legs (5 mm i.d. × 8 mm o.d.). Each leg extends 17 cm from a 4–cm o.d. hollow hub that serves as a vacuum manifold and is mounted in the center of each tunnel. The end of each leg is plugged to allow air entry through three holes that are drilled at distances of 70, 140, and 180 mm from the center of the tunnel with corresponding diameters of 3.0, 4.0, and 4.4 mm, respectively (Lockyer, 1996). The six–legged "star sampler" is mounted in the center of each tunnel with a threaded stainless steel support tube (10.5 mm i.d. and 12.5 mm o.d.) extending from the top of the tunnel (fig. 2) and containing a $90°$ bend to expose the sampler to the cross section of the tunnel. The threaded support tube allows positioning of the sampler in the center of the tunnel and also serves as a section of vacuum line connecting the sampler to the outlet gas–scrubbing bottle.

Ammonia concentrations in the entering and exiting air streams (ug N m^{-3} of air) are measured using gas scrubbing bottles, flow meters, and vacuum pumps. The gas scrubbing bottles (Kontes Glassware, Vineland, N.J.) contain a dispersion tube with a coarse texture glass frit and utilize 0.002 mol L^{-1} H$_3$PO$_4$ to trap ammonia. A 125–mL bottle, containing 80 mL of acid, is used on each inlet and a 250–mL bottle, containing 120 mL of acid is used on each outlet. These quantities of acid minimize acid movement into vacuum lines while maintaining a complete immersion of the gas dispersion frit. The inlet gas scrubbing bottle is placed directly in front of the canopy entrance with air entering at a 20 cm height while the outlet gas bottle is connected to the "star sampler" with 1.3 m of 12.8–mm i.d. tygon tubing containing an FEP Teflon lining (Cole Parmer Inc., Part No.

U–95711–40, Vernon Hills, Ill.). The Teflon lining prevents ammonia loss that can occur with unlined tygon. The Teflon–lined suction tubing was not used on the inlets because inlet air directly enters the gas–scrubbing bottle. The volume of air passing through the gas scrubbing bottles is measured with an adjustable rotometer gas–flow meter (Gilmont Inst., model GF5321–2410 65 mm for inlets, model GF5522–2717 150 mm for outlets, Barrington, Ill.). The flow meters are connected to the washing bottles with tygon tubing and are mounted vertically using conventional laboratory clamps and steel rods secured to a wooden platform. One dual–channel diaphragm vacuum pump (Thomas Pumps Inc., model 2107CA20, Grainger Supply Co., Washington, D.C.), capable of flows up to 6 L min^{-1} channel^{-1}, is used to sample air from the inlet and outlet air streams. The pump is set on a foam rubber pad (to dampen vibrations) and is placed on the same wooden platform as the flow meters, adjacent to each tunnel.

Airflow rates through the body of each tunnel were calibrated with a balometer, while air flows through individual gas scrubbers were calibrated with a gas mass–flow meter. The balometer (Alnor Inc., model 151, Skokie, Ill.) was the type used to measure airflow in air circulation systems and consists of a series of pitot tubes connected to a central pressure transducer and data processor. Wind tunnel airflow calibration involved placing the balometer firmly against the tunnel discharge, adjusting motor rpm to the desired level, allowing several minutes for stabilization, and recording the balometer reading along with the accompanying thermal anemometer reading. This process was repeated for 8 calibration points from 0.5 to 4 m s^{-1}. The calibration produced highly significant linear calibration curves (R$^2 > 0.995$) for each tunnel. There was no significant difference in calibration equations between individual tunnels. The final average equation was: Y = 3.3 + 142.5(X); where Y is total airflow (L s^{-1}) and X is the thermal anemometer reading (m s^{-1}). The flow meters for the gas scrubbing bottles were calibrated with a Teledyne gas mass–flow meter (Teledyne Hastings–Raydist Instr., model NALL–10K, Hampton, Va.). Flow meter calibration involved adding acid to the scrubbers, connecting the scrubber to the flow meter and vacuum pump, and recording the mass flow meter value and accompanying flow–meter reading after stabilization. This process was repeated for 5 calibration points that spanned the normal operation range. Highly significant linear relations (r > 0.95) were obtained between mass flow (L min^{-1}) and individual flow meter readings, but a single average relationship could not be used for all flow meters. Therefore, individual calibration equations were used for each scrubber when data were calculated.

OPERATION

Tunnel set–up involved attaching all electrical connections to power supplies and data loggers, applying the required treatments to the canopy area, immediately placing the canopy over the treated area and securing it to the cowling, activating and adjusting the dc motor to the desired wind speed, connecting the gas scrubber bottles, activating the pumps, and adjusting the flow meters to target flow rates. Generally, measurements commence within 15 min of completing treatment application. The treatments are

normally applied to a 1.7 m length of the 2–m canopy, leaving a 0.3–m untreated area in the entrance of each tunnel which serves to stabilize air flow and minimizes counter–current diffusion (Harper, 1996). Potential air leaks between the canopy base frame and the ground are minimized by tightly packing soil against the canopy base frame. If used indoors, the canopy is sealed to the floor with duct tape.

Sampling intervals can vary from a few hours to 24 h depending on the degree of expected ammonia evolution. Normal practice is to sample every 4 to 6 h during the day, i.e. over the morning hours, the afternoon hours, and to sample once over the 12 to 16 h of evening–night conditions. This sampling procedure is useful to document diurnal variations. The upper limit of exposure time is dictated by evaporative loss of water in the acid trap solution, enough solution should be present to completely immerse the gas dispersion tube frits. The lower exposure time is dictated by the limits of the NH_4–N analytical methods and the desire to have outlet ammonia concentrations higher than the background inlet concentrations.

DATA CALCULATIONS

Ammonia loss for each wind tunnel is calculated by multiplying the increase in ammonia concentration from the inlet to the outlet air streams by the total airflow rate through the tunnel. The NH_3–N concentration in the inlet and outlet air streams (ug N m^{-3} of air) is calculated from the input data of NH_4–N concentration in the acid traps, volume of acid, exposure time, and the average flow meter readings which are converted to air volume through the flow–meter calibrations. Total airflow through the tunnel is calculated from the average thermal anemometer readings over the exposure time and the balometer calibration equation. The average ammonia flux (mass N $area^{-1}$ $time^{-1}$) can be estimated by dividing the mass of ammonia lost by the treatment area and the exposure time. Cumulative losses over time are also routinely calculated with losses expressed as a percentage of the applied ammonium–N.

VALIDATION MATERIALS AND METHODS

AMMONIA RECOVERY STUDY

The ability of the tunnels to recover ammonia was evaluated by conducting a mass balance loss–and–recovery experiment. The same procedures described above were followed except they were conducted indoors in a small heated building, with all six tunnels placed side–by–side. The building contained 500 m^3 of air and was equipped with an exhaust fan that was activated at intervals to give four building air–exchanges every hour. The exhaust fan discharged volatilized ammonia and lowered the inlet ammonia concentrations well below the outlet concentrations. A manually read mercury maximum–minimum thermometer was also hung in the entrance of each canopy to document individual canopy temperatures. The humidity and temperature at a 1 m height on each side of the group of tunnels was also continuously recorded on hygrothermograph (Belfort Instr., model 5–594, Baltimore, Md.).

The general approach was to measure the loss of NH_4–N from alkaline solutions placed in the tunnel canopies and compare the losses to the quantity of N recovered by the tunnels. Two plastic "cafeteria trays" (63 × 43 × 2 cm deep,

5 L capacity) were placed under each canopy and each filled with 3 L of alkaline solution containing ammonium sulfate. The trays were placed in the middle of the canopy, leaving 0.3 m in the front and 0.4 m in the rear to serve as "buffer areas" to minimize air turbulence. The alkaline solution was a buffer solution of 0.087 mol K_2HPO_4 L^{-1}, 0.013 mol KH_2PO_4 L^{-1}, 0.01 mol NaOH L^{-1}, to which was added 0.0119 mol $(NH_4)_2SO_4$ L^{-1}. These reagents and concentrations produced a mildly buffered solution with an initial pH of 8.2–8.3 and an initial total ammoniacal N concentration of about 333 mg NH_4–N L^{-1}. A pH in the range of 8–8.5 was selected because it is similar to the pH of dairy slurries or poultry litter; it is also close to the pH of ammonium carbonate, which is the first hydrolysis product of urea. The buffer solutions were prepared ahead of time and the ammonium sulfate was added immediately before pouring the mixture into the trays. Samples of the starting solutions from each tray were taken for determination of total ammoniacal N and pH. The target wind speeds were 0.5 m s^{-1} (trial A) and 1.0 m s^{-1} (trial B). Scrubber flow–meter rates were 3 L min^{-1} for the inlets and 3.5 L min^{-1} for the outlets. Experiments were run for 44 h with gas scrubber samples collected after 5 h, 20 h, and at the end of the experiment. At each sampling time flow meter readings were recorded before changing acid along with maximum–minimum temperatures, after changing acid flow meters were readjusted to the above flow rates. After collection, the scrubber acid was made up to volume, 100 mL for inlets and 250 mL for outlets, with 0.002 mol L^{-1} H_3PO_4 and refrigerated until analysis.

The loss of ammoniacal–N from the trays during each experiment was determined by measuring the mass of solution at the start and the end of each experiment and by collecting corresponding samples of the solutions for ammoniacal–N analysis. The buffer solutions in each tray were sampled before each experiment by removing a 10–mL sub–sample, diluting to 100 mL with H_3PO_4, and refrigerating until analysis. At the conclusion of each experiment the volume of buffer solution was determined by weighing each tray, the solution was quantitatively rinsed out of each tray, brought to a known volume with pure water, mixed, and a 10 mL sub–sample was taken and diluted to 100 mL with H_3PO_4 and refrigerated. These data allow calculation of ammonia volatilization and water loss from the individual trays.

ANALYTICAL METHODS

Total ammoniacal N in the tray buffer solutions was determined by steam distillation (Keeney and Nelson, 1982) of a 5–mL aliquot using excess NaOH to make the solutions basic, as shown by a few drops of phenolphthalein indicator. In this procedure the distilled ammonia is trapped in 2% boric acid and titrated with standard 0.005 N H_2SO_4. The steam distillation method was chosen for the buffer solutions because of the high NH_4–N concentrations.

Ammoniacal N from the gas scrubbing bottles was determined by the Berthelot's indophenol blue method using sodium salicylate as phenolic reagent (Kempers and Zweers, 1986). The samples and accompanying standards were allowed to react with reagents for 1 h at room temperature after which color intensity was measured with a Brinkman model 801 fiber optic colorimeter (Brinkman Instruments

Inc., Westbury, N.Y.) using a 650–nm filter and a 4–cm path length total immersion fiber optic probe. The linear operating range of this method was 10 to 500 ug NH_4–N L^{-1}, with a sensitivity of ±10 ug NH_4–N L^{-1}. The indephenol blue method was employed because of its excellent sensitivity below 100 ug NH_4–N L^{-1}. Two different NH_4–N analysis methods were used because of the extreme difference in NH_4–N concentrations between the buffer trays (330 mg NH_4–N L^{-1}) and the gas scrubbers (0.1 mg NH_4–N L^{-1}). Consistency between the methods was assured by regular analysis of a quality control (QC) NH_4–N standard, recoveries of the QC standard were always 98% or higher for each method. Buffer solution pH was determined with a glass–calomel combination electrode using an Orion model 920A pH meter.

RESULTS AND DISCUSSION

GENERAL RESULTS

The material and construction costs of each wind tunnel were about $4000 (table 1), which can be pro–rated to an annual cost of about $500 if the tunnels have an eight–year life expectancy. However, table 1 also reveals several areas where cost savings could be realized. For example, the variable speed dc motor and custom fan blade could be replaced by a smaller ac motor and conventional blade if only moderate (0.5 to 1.5 m s^{-1}) and non–adjustable wind velocities are required.

The process of construction, calibration, and operation of the wind tunnels also revealed several critical areas: i) all tubing connections need to be securely clamped to each apparatus to minimize air leaks, ii) it is essential to calibrate individual gas scrubber flow meters, iii) tunnel wind speeds need to be continuously monitored, and iii) it is essential to have pure water and to be meticulously clean (using rubber gloves, clean sample bottles, etc.) when working with the gas scrubber acid solutions. Quality control samples, i.e. reagent blanks and NH_4–N standards, should also be utilized throughout each experiment.

LOSS AND RECOVERY EXPERIMENTS

Two loss–and–recovery experiments were conducted, one at nominal wind speeds of 0.5 m s^{-1} and one at 1.0 m s^{-1}. These wind speeds, and the constant speed mode, were selected because they represent the normal operating conditions of wind–tunnel research (Lockyer, 1984; Lorenz and Steffens, 1997; Moal et al., 1995; Thompson et al., 1987; Thompson et al., 1990). The higher wind speed and adjustability features of these tunnels will be employed in later experiments.

Trial A, 0.5 m s^{-1} Velocity

The results of the first 0.5 m s^{-1} loss–and–recovery experiment (table 2) shows excellent tunnel recovery of the volatilized ammonia. The average recovery was 104% $\pm6\%$ across the six tunnels, the CV among tunnels was 6%. Ammonia volatilization and water evaporation was lowest for tunnel one with increases occurring for tunnels four to six. These differences were evidently due to a temperature

Table. 2. Trial A ammonia loss–and–recovery data for six wind tunnels operated at wind speeds of 0.5 m s^{-1} with average ambient temperature of 12.8°C[a].

Tunnel No.	Total Losses from Trays		Tunnel Recoveries		Tunnel Individual Regression Statistics		
	Water (L)	NH_3-N (mg N)	NH_3-N (mg N)	(%)	Intercept (mg NH_3-N)	Slope (mg NH_3-N/h)	R^2
1	1.34	291	287	99	21 ±26	6.5 ±1.1	0.92
2	1.49	360	380	106	-6 ±18	8.5 ±0.7	0.98
3	1.50	335	367	110	18 ±15	8.2 ±0.6	0.98
4	1.61	403	410	102	-2 ±23	9.0 ±0.9	0.97
5	1.71	388	434	112	18 ±17	9.8 ±0.7	0.99
6	1.64	406	400	98	16 ±13	9.0 ±0.5	0.99
Statistics across tunnels :							
Mean:	1.55	364	380	104	11	8.5	---
SD:	0.13	45	51	±6	±12	±1.1	---
CV:	9%	12%	13%	6%	---	---	---

[a] Initial NH_4-N solution in each tunnel contained 334 mg N L^{-1} at pH 8.26; final solution contained 369 mg N L^{-1} at pH 7.83.

differential of about 1°C, with tunnel one being cooler than tunnels four to six. The cooler temperatures for tunnel one resulted from its location adjacent to a non–insulated outside wall of the building, while tunnels four to six were in the center of the building closer to the heating unit. The temperature gradient also produced a gradient in relative humidity (65% for tunnel one vs. 59% for tunnels four to six). The slightly higher temperature and lower relative humidity provided a larger evaporative force for tunnels four to six. This is illustrated in the water loss data from the trays (table 2, col. 2) where tunnel one lost about 1.34 L while tunnels four to six averaged losses of 1.65 L. Ammonia losses from tunnel one were also correspondingly lower than tunnels four to six (table 2, col. 3). The lower evaporative conditions of tunnel one also explain the slightly smaller slope in the cumulative NH_3–N versus time relationship (table 2, col. 7). Another noteworthy observation was a 5% greater loss of water and ammonia from the tray placed closest to the inlet end of the canopy (data not shown). The pH of the buffer solutions began at 8.3 and ended at 7.8 (table 2, footnote) because ammonia volatilization removes the basic NH_3 molecule, leaving behind a more acidic solution. However, the buffer capacity of the exposed solution kept the pH from falling below 7 and therefore did not stop ammonia volatilization during the 44–h trial.

Trial B, 1.0 m s^{-1} Velocity

The results of the second trial, at nominal velocities of 1.0 m s^{-1}, also show very good tunnel recovery of the volatilized ammonia (table 3). The average recovery was 104% $\pm18\%$ across the five tunnels, and the CV among tunnels was 17%. The data for tunnel four was lost due to a vacuum pump failure. The second trial successfully recovered the volatilized ammonia, but there was about three times more variability among tunnels than the 0.5 m s^{-1} trial. Part of the added variability is likely due to a greater degree of air turbulence at the higher wind speeds. The water evaporation and ammonia volatilization was again lowest for tunnel one and highest for tunnels five and six. These differences were due to a 1.5°C lower temperature for tunnel one, adjacent to the outside wall, compared to tunnels five and six. The temperature differences also produced relative humidity differences (69% for tunnel one compared to 64%

Table. 3. Trial B ammonia loss–and–recovery data for five wind tunnels operated at wind speeds of 1.0 m s⁻¹ with average ambient temperature of 14.2°C[a].

Tunnel No.	Total Losses from Trays		Tunnel Recoveries		Tunnel Individual Regression Statistics		
	Water (L)	NH$_3$-N (mg N)	NH$_3$-N (mg N)	(%)	Intercept (mg NH$_3$-N)	Slope (mg NH$_3$-N/h)	R^2
1	1.77	473	463	98	25 ±31	10.4 ±1.3	0.96
2	1.70	550	742	135	-11 ±27	17.3 ±1.1	0.99
3	1.76	511	529	104	52 ±37	11.2 ±1.5	0.95
5	2.24	630	609	97	30 ±27	13.6 ±1.1	0.98
6	2.23	576	504	87	31 ±25	11.1 ±1.0	0.98
Statistics across Tunnels:							
Mean	1.94	548	569	104	25	12.7	---
SD	0.27	60	110	±18	±23	±2.8	---
CV	14%	11%	19%	17%	---	---	---

[a] Initial NH$_4$-N solution in each tunnel contained 332 mg N/L at pH 8.28; final solution contained 356 mg N/L at pH 7.73.

for tunnels five and six) and a larger evaporative driving force for tunnels five and six. The tray water loss data and ammonia loss data (table 3, col. 2 and 3) also show higher losses for tunnels five and six, as in the first trial. The local temperature and humidity effects, observed in both trials, illustrate that ammonia volatilization is closely dependent upon local physical conditions. As in the first trial, the front tray in all tunnels lost an average of 5% more water and ammonia than the back tray (data not shown) and the pH of the ammonium sulfate solution also fell about 0.5 units (table 3, footnote).

Combined Observations

Both of the above trials produced highly satisfactory results with ammonia recoveries averaging a little over 100%. However, higher wind velocities did increase the variability among tunnels, a likely result from greater air turbulence and/or the effects of a somewhat larger temperature differentials across the tunnels. There was a close association between water evaporation and ammonia volatilization in both studies, as shown by the correspondence between tray water loss and tray ammonia loss (compare col. 2 and 3 in tables 2 and 3). The statistical relationship between water loss (X, in L) and ammonia loss (Y, in mg N) for individual trays (data not shown) was Y = –37 (SE±30) +302 (SE±34) X, which produced a highly significant correlation coefficient of 0.89 (R^2 = 0.79). Another noteworthy feature is the influence of average experiment temperature and relative humidity conditions. For example, at 0.5 m s⁻¹ average water loss was 1.55 L compared to 1.94 L at 1.0 m s⁻¹ (25% higher loss), while average ammonia losses were 364 mg N at 0.5 m s⁻¹ compared to 548 mg N at 1.0 m s⁻¹ (a 50% increase). Of course, part of the higher losses in the second trial is attributed to higher wind velocities, but some of the added loss can also be ascribed to higher experimental temperatures. The average indoor temperature for trial B was 14.2°C compared to 12.8°C for trial A (see headings of tables 2 and 3). Data from both trials illustrate that ammonia volatilization is a process easily influenced by only modest perturbations in physical conditions such as wind and temperature.

SUMMARY AND CONCLUSIONS

Ammonia volatilization is a major N loss process for surface applied manures and urea fertilizers. A detailed description of the design, construction, cost, and physical calibration of small mobile wind tunnels originally introduced by Lockyer (1984) is given. The tunnels utilize a canopy covered 1–m² treatment area connected to a sheet–metal cylinder housing an adjustable speed motor and fan, plus an air sampler which can monitor ammonia volatilization over time. The tunnels are moderately priced (about $4000 each), are fully independent, allow treatment replication, and allow relative comparisons among experimental treatments. Two loss–and–recovery experiments were conducted at constant wind speeds of 0.5 and 1.0 m s⁻¹ to assess tunnel performance. Ammonia recoveries averaged 104% ± 6% at 0.5 m s⁻¹ and 104% ± 18% at 1.0 m s⁻¹. These results demonstrate that the wind tunnels can quantitatively recover ammonia lost from alkaline solutions. Therefore, wind tunnels are valid tools for collecting volatilized ammonia and making relative comparisons among N management treatments, which is essential in developing N management practices to minimize ammonia losses from manures or fertilizers.

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